



Techno-economic assessment and optimization of Stirling engine micro-cogeneration systems in residential buildings

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ABSTRACT

Micro-cogeneration offers numerous potential advantages for the supply of energy to residential buildings in the sense of improved energy efficiency and reduced environmental burdens. To realize these benefits, however, such systems must reduce energy costs, primary energy consumption, and CO₂ emissions relative to conventional heating systems. In this paper, we search for optimized strategies for the integration of a Stirling engine-based micro-cogeneration system in residential buildings by comparing the performance of various system configurations and operational strategies with that of a reference system, i.e. hydronic heating and a low temperature gas boiler in standard and passive house constructions located in different climates. The IDA-ICE whole-building simulation program is employed with the Stirling engine micro-cogeneration model that was developed by IEA/ECBCS Annex 42. In this way the dynamic effects of micro-cogeneration devices, such as warm-ups and shutdowns, are accounted for. This study contributes to the research by addressing hourly changes in the fuel mix used for central electricity generation and the utilization of thermal exhaust through heat recovery. Our results suggest that an optimally operated micro-cogeneration system encompassing heat recovery and appropriate thermal storage would result in a 3–5% decrease in primary energy consumption and CO₂ emissions when compared to a conventional hydronic heating system. Moreover, this configuration is capable of delivering annual savings in all the combinations of electricity and fuel price between 0.05 and 0.15 € kW h^{−1}. As can be expected, these results are sensitive to the electrical energy supply mix, building type, and climate.

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1. Introduction

The building sector accounts for approximately 40% of primary energy use and 36% of total CO₂ emissions in most developed countries [1]. Nowadays both research and policy development strongly support improving the energy efficiency of energy systems and promoting the use of sustainable sources of energy, which, in turn, requires efforts on both the energy supply and demand sides. Traditional energy-saving measures related to building envelopes and fenestration are well-established, whereas much current research focuses on energy management, the integration of building services, and on-site energy generation [2,3].

Micro-cogeneration, i.e. the local generation of electrical and thermal power simultaneously to satisfy the power demands of lighting, appliances, and building services plus the thermal demands of space heating and production of hot water in residential buildings, is an alternative to conventional oil, gas, and biomass boilers, and, to some extent, heat pumps, solar thermal, and photovoltaic systems. Advantages accrue both in terms of improved en-

ergy efficiency and reduced environmental burdens, provided that the systems operate in an energy-efficient manner, i.e. the match between electrical and thermal power demand and supply is reached at a local level [3].

The most cited technologies in small-scale micro-cogeneration (less than 5 kW_e) are fuel cells, internal combustion engines, and Stirling engines. While fuel cells offer promise for the future in terms of electrical conversion efficiency, noise, and emissions, the combustion-based technologies are more technically mature and closer to market. One notable advantage offered by Stirling engines is their ability to combust a variety of fuels, such as petroleum and biomass-based fuels [4,5].

Performance assessment is an approach to the evaluation of the viability of micro-cogeneration systems in comparison with the alternative options for residential energy supply, and thus a way to develop more energy-efficient systems that rise to the challenges of increasing competition on the market. The basic criteria are reductions in life-cycle costs, primary energy, and CO₂ emissions. At the moment, the first method for the above task is a computational study based on the simulation of a whole building. A significant effort was made in terms of Annex 42 of the International Energy Agency's Energy Conservation in Buildings and

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Acronyms and abbreviations

CHP	combined heat and power	PER	primary energy conversion factor
DHW	domestic hot water	SE	Stirling engine
ECBCS	Energy Conservation in Buildings and Community Systems Program	SOFC	solid-oxide fuel cell
IDA-ICE	Indoor Climate and Energy	TOTPE	total primary energy
IEA	International Energy Agency	UCPTE	Union for the Co-ordination of Production and Transmission of Electricity
LHV	lower heating value		
NRPE	Non-Renewable Primary Energy		

Community Systems Program (IEA/ECBCS), in which simulation models for this purpose were developed [6], calibrated, and validated [7].

The results of performance assessments conducted to date for the current generation of Stirling engine micro-cogeneration devices suggest that a Stirling engine application may result in an increase of 5–24% in non-renewable primary energy use and to a reduction of 20% in CO₂ emissions at a maximum [3,8–10]. The outcome of this type of analysis strongly depends on climatic conditions and local building standards, which makes performance assessments country-specific. Moreover, issues such as how the primary energy and emission factors for different energy sources are determined may substantially affect the applicability of the results. For the above reasons, merely leaning on the earlier assessments dealing with the viability of micro-cogeneration may easily result in misleading conclusions and uncertainty analysis is needed.

In this paper, we search for optimized strategies for the integration of Stirling engine-based residential micro-cogeneration systems in the sense of performance assessment, focusing on two issues that hitherto have not been widely discussed, namely: (i) time-dependent changes in the energy generation mix and (ii) the utilization of thermal exhaust through heat recovery in the pre-heating of the supply air. As a result of the optimization, we expect to establish appropriate control strategies for micro-cogeneration equipment, optimal sizes for storage tanks, and the effect of heat recovery from the exhaust gases with the aims of minimizing the use of grid electricity on an annual basis and of minimizing the dumping of thermal energy. The present study only focuses on micro-cogeneration for the supply of energy to single buildings. The impact of local grids, where more than one building is served by one micro-cogeneration plant, is not examined. The simulation results represent Finnish conditions, but the methodology could be extended to other locations.

2. Methodology

2.1. Evaluation procedure

The performance evaluation procedure takes place in three phases. First, the Stirling engine-based micro-cogeneration system is modeled and simulated in the IDA-ICE building simulation program, where the Stirling engine routine is implemented following the model specifications of IEA/ECBCS Annex 42 [6]. The aim of these simulations is to identify the system configurations and operational strategies with minimum annual thermal loss and grid electricity.

Second, the annual costs, primary energy use, and CO₂ emissions of selected alternatives are determined by post-processing the simulation results. This analysis allows conclusions to be drawn about the performance of micro-cogeneration alternatives with respect to that of the reference system, i.e. hydronic heating

and a condensing gas boiler in standard and passive house constructions located in different climates.

Finally, the sensitivity of the results to energy prices and primary energy and emission coefficients is investigated and recommendations on the most viable alternatives are given.

2.2. Simulation platform

Dynamic and whole-building simulation is applied in computational analysis because of: (i) the dynamic effects incorporated in micro-cogeneration systems, such as warm-ups and shutdowns and (ii) the effects of a micro-cogeneration plant on the thermal processes occurring in the building and vice versa (e.g. [11,12]). IDA-ICE (Indoor Climate and Energy) has been selected as a simulation tool, because it is an advanced building simulation tool and widely used in the Nordic Countries for both commercial and research purposes, providing dynamic simulation for heat transfer, internal and solar gains, and airflows in buildings. The program was developed by the Royal Institute of Technology and the Swedish Institute of Applied Mathematics. The details are given in [13,14], and test studies are reported for various applications in [15,16].

2.3. Annex 42 model

This section reviews pertinent aspects of the Annex 42 model. The reader is referred to [7,17] for a detailed treatment. Annex 42 of the International Energy Agency (IEA) developed “grey-box” models that: (i) account for the thermal, chemical, and electrical phenomena necessary to properly depict processes in the sense of building simulation and (ii) support the integration of micro-cogeneration technologies into a broader context in building services. Routines for both fuel cell- and combustion engine-based micro-cogeneration were developed and so far they have been implemented into the ESP-r, TRNSYS, and EnergyPlus simulation programs. These implementations have been validated both by several empirical runs and inter-program tests [6]. Before the present study, the only implementation of Annex 42 models into IDA-ICE was a routine for a solid-oxide fuel cell (SOFC) [18].

The Annex 42 model, well-rooted in the work of McCrorie et al. [19], Kelly [20], and Pearce et al. [21], is capable of representing either internal combustion engine (ICE) or Stirling engine (SE) micro-cogeneration devices. Considering that a plant consists of a generator linked to the engine, and a gas-to-water heat exchanger and ancillaries such as water circulation pumps and control systems, the device model encompasses three main control volumes: (i) the energy conversion control volume, which expresses the conversion of fuel to electricity and heat in the engine under steady-state conditions; (ii) the thermal mass control volume, which represents the thermal mass or the thermal capacitance of the engine as a whole; and (iii) the cooling water control volume, which characterizes the heat exchange between the exhaust gas and the

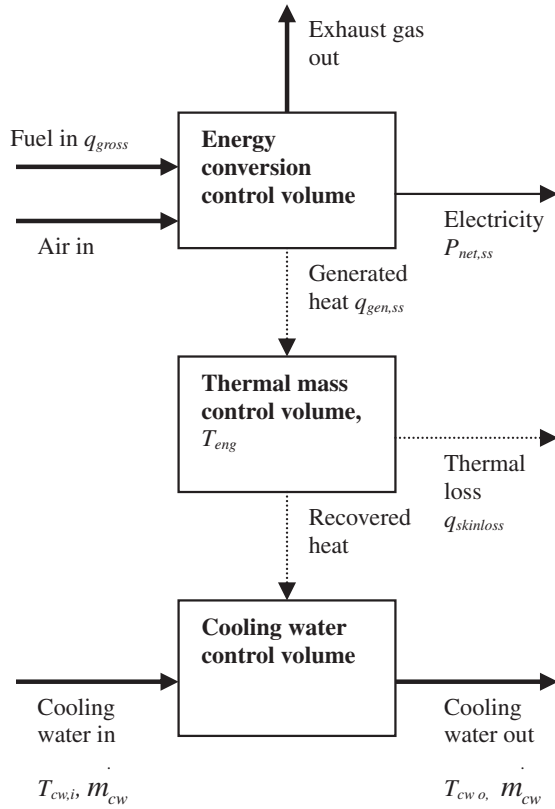


Fig. 1. Control volumes associated with Annex 42 model.

cooling water and all engine parts in immediate thermal contact. The control volumes of the Annex 42 model are shown in Fig. 1.

The most useful simplification in the Annex 42 model is that the exact analysis of physical and chemical phenomena such as the combustion process and thermodynamic cycles has been omitted and replaced by engine-specific, empirical correlations that rely on measured data. The Annex 42 model contains 27-term tri-variate polynomials to express the thermal and electrical efficiencies of the plant [17], even though calibration studies conducted to date have indicated that some of these terms may be unnecessary. The parameterized efficiencies are given in Eqs. (1) and (2):

$$\begin{aligned} \eta_e = & a_0 + a_1 P_{net,ss}^2 + a_2 P_{net,ss} + a_3 \dot{m}_{cw}^2 + a_4 \dot{m}_{cw} + a_5 T_{cw}^2 + a_6 T_{cw} \\ & + a_7 P_{net,ss}^2 \dot{m}_{cw}^2 + a_8 P_{net,ss} \dot{m}_{cw}^2 + a_9 P_{net,ss} \dot{m}_{cw}^2 + a_{10} P_{net,ss} \dot{m}_{cw} \\ & + a_{11} P_{net,ss}^2 T_{cw}^2 + a_{12} P_{net,ss} T_{cw}^2 + a_{13} P_{net,ss} T_{cw}^2 + a_{14} P_{net,ss}^2 T_{cw} \\ & + a_{15} \dot{m}_{cw}^2 T_{cw}^2 + a_{16} \dot{m}_{cw} T_{cw}^2 + a_{17} \dot{m}_{cw} T_{cw}^2 + a_{18} \dot{m}_{cw}^2 T_{cw} \\ & + a_{19} P_{net,ss}^2 \dot{m}_{cw}^2 T_{cw}^2 + a_{20} P_{net,ss}^2 \dot{m}_{cw}^2 T_{cw} + a_{21} P_{net,ss}^2 \dot{m}_{cw} T_{cw}^2 \\ & + a_{22} P_{net,ss} \dot{m}_{cw}^2 T_{cw}^2 + a_{23} P_{net,ss}^2 \dot{m}_{cw} T_{cw} + a_{24} P_{net,ss} \dot{m}_{cw}^2 T_{cw} \\ & + a_{25} P_{net,ss} \dot{m}_{cw} T_{cw}^2 + a_{26} P_{net,ss} \dot{m}_{cw} T_{cw} \end{aligned} \quad (1)$$

$$\begin{aligned} \eta_q = & b_0 + b_1 P_{net,ss}^2 + b_2 P_{net,ss} + b_3 \dot{m}_{cw}^2 + b_4 \dot{m}_{cw} + b_5 T_{cw}^2 + b_6 T_{cw} \\ & + b_7 P_{net,ss}^2 \dot{m}_{cw}^2 + b_8 P_{net,ss} \dot{m}_{cw}^2 + b_9 P_{net,ss} \dot{m}_{cw}^2 + b_{10} P_{net,ss} \dot{m}_{cw} \\ & + b_{11} P_{net,ss}^2 T_{cw}^2 + b_{12} P_{net,ss} T_{cw}^2 + b_{13} P_{net,ss} T_{cw}^2 + b_{14} P_{net,ss}^2 T_{cw} \\ & + b_{15} \dot{m}_{cw}^2 T_{cw}^2 + b_{16} \dot{m}_{cw} T_{cw}^2 + b_{17} \dot{m}_{cw} T_{cw}^2 + b_{18} \dot{m}_{cw}^2 T_{cw} \\ & + b_{19} P_{net,ss}^2 \dot{m}_{cw}^2 T_{cw}^2 + b_{20} P_{net,ss}^2 \dot{m}_{cw}^2 T_{cw} + b_{21} P_{net,ss}^2 \dot{m}_{cw} T_{cw}^2 \\ & + b_{22} P_{net,ss} \dot{m}_{cw}^2 T_{cw}^2 + b_{23} P_{net,ss}^2 \dot{m}_{cw} T_{cw} + b_{24} P_{net,ss} \dot{m}_{cw}^2 T_{cw} \\ & + b_{25} P_{net,ss} \dot{m}_{cw} T_{cw}^2 + b_{26} P_{net,ss} \dot{m}_{cw} T_{cw} \end{aligned} \quad (2)$$

where η_e and η_q are the electrical and the thermal efficiencies, respectively, $a_0 \dots a_{26}$ and $b_0 \dots b_{26}$ are empirical constants, and $\dot{m}_{cw}$

and $T_{cw,i}$ are the mass flow and temperature of the cooling water supplied to the device, respectively. The incomplete steady-state combustion is now given as:

$$q_{gross} = \dot{m}_{fuel} LHV_{fuel} \quad (3)$$

$$P_{net,ss} = \eta_e q_{gross} \quad (4)$$

$$q_{gen,ss} = \eta_q q_{gross} \quad (5)$$

where q_{gross} is the gross thermal input to the system, $\dot{m}_{fuel}$ is the fuel flow, LHV_{fuel} is the lower heating value of the fuel, q and e are the net thermal and electrical conversion efficiencies, respectively, $P_{net,ss}$ is the steady-state electrical output, and $q_{gen,ss}$ is the steady-state heat flow released by the combustion that is transferred to the thermal mass control volume, i.e. the gross thermal input minus the non-utilizable thermal loss to the ambient air through exhaust gases.

Heat transfer takes place from exhaust gases to the cooling water flow and from the engine to the ambient air. The engine is considered one thermal capacity MC_{eng} with an average temperature T_{eng} . The encapsulated cooling water comprises another thermal capacity MC_{cw} , the temperature of which is the bulk temperature of the cooling water control volume, i.e. the outlet temperature $T_{cw,o}$. Inlet temperature being $T_{cw,i}$, the governing balance equation for heat transfer between the engine and the ambient air is

$$MC_{eng} \frac{dT_{eng}}{dt} = UA_{HX}(T_{cw,o} - T_{eng}) + UA_{loss}(T_{amb} - T_{eng}) + q_{gen,ss} \quad (6)$$

where UA_{HX} and UA_{loss} are engine-specific, empirically determined heat transfer coefficients. Correspondingly, the heat transfer between the engine and the cooling water can be expressed as

$$MC_{cw} \frac{dT_{cw,o}}{dt} = \dot{m}_{cw} \dot{c}_{p,cw}(T_{cw,i} - T_{cw,o}) + UA_{HX}(T_{eng} - T_{cw,o}) \quad (7)$$

The engine model supports three modes of operation: (i) steady-state functioning; (ii) engine warm-up; and (iii) cool-down. Furthermore, the rate of change in the electrical power per time unit may be limited. In cool-down and standby modes, the plant does not generate heat or electricity, but consumes electrical power at a fixed rate to maintain functions related to the activation or deactivation of the device. During warm-up, a limited amount of electricity and thermal power is produced, depending on the operational temperatures of the Stirling engine. Here, the power output during this period is approximated as

$$P_{net,warm-up} = P_{max} k_p \left(\frac{T_{eng} - T_{amb}}{T_{eng,nom} - T_{amb}} \right) \quad (8)$$

where P_{max} is the steady-state maximum power for the engine, k_p is an empirical coefficient, and $T_{eng,nom}$ is the nominal operating temperature. A peak then occurs in the fuel flow and is calculated in the model from

$$\dot{m}_{fuel} = \dot{m}_{fuel,ss} + k_f \dot{m}_{fuel,ss} \frac{T_{eng,nom} - T_{amb}}{T_{eng} - T_{amb}} \quad (9)$$

where $\dot{m}_{fuel,ss}$ is the fuel flow in steady-state conditions and k_f is an empirical parameter. Empirical calibration parameters are required by Eqs. (1)–(9). These parameters have been established for a prototype Stirling engine micro-cogeneration device by Beausoleil-Morrison [6] and Ferguson [7]. These parameters are used in the present study. Hence the system under consideration represents the performance characteristics of currently available Stirling engine micro-cogeneration devices.

2.4. Extension of Annex 42 model to consider heat recovery from exhaust gases

In the present study, the utilization of waste heat is investigated in terms of pre-heating the supply air and/or combustion air. The enthalpy flow of the exhaust outlet is first determined from the steady-state energy balance for the energy conversion control volume and is defined as

$$\dot{H}_{exh} = (1 - \eta_q)q_{gross} - P_{net,ss} \quad (10)$$

On the basis of the Shomate equation [22], the enthalpy flow is also

$$\dot{H}_{exh} = \frac{AT_{exh}}{1000} + \frac{B}{2} \left(\frac{T_{exh}}{1000} \right)^2 + \frac{C}{3} \left(\frac{T_{exh}}{1000} \right)^3 + \frac{D}{4} \left(\frac{T_{exh}}{1000} \right)^4 + E \frac{1000}{T_{exh}} \quad (11)$$

where $A, B, \dots, E$ are coefficients for each constituent of the exhaust gas. The temperature T_{exh} is now solved from Eq. (11) and applied as an input parameter for the heat recovery model of IDA-ICE.

2.5. Implementation and validation of the IDA-ICE model

The combustion engine model was implemented in IDA-ICE and validated by way of comparative testing with Energy Plus, ESP-r, and TRNSYS, following the Annex 42 testing program, which encompasses nine test series including a total of 44 separate cases [23]. The present implementation obtained excellent agreement with the above tools. The validation process as a whole is reported in [24].

2.6. Performance assessment

The performance of alternative micro-cogeneration strategies is evaluated in terms of annual primary energy use and CO₂ emissions. Primary energy use is calculated by multiplying the annual energy consumption of each energy carrier (thermal and electrical energy) by a specific primary energy conversion factor (PER) that indicates the amount of primary energy needed to produce one kilowatt hour of supplied energy at the boundary of the consumption site. Hence, primary energy use represents the real burden related to energy supply, including the fuel's chemical energy plus all the losses caused by the conversion and delivery of each form of energy. The emissions of carbon dioxide are computed equivalently, on the basis of annual energy consumption and a specific carbon dioxide emission factor (CO₂) [25].

Primary energy and carbon dioxide methods provide a simple and relatively accurate tool to predict the performance in terms of sustainability. On the other hand, the approach is rather inflexible [26]. Both factors depend on the national energy mix, which varies over time as a result of peak demands. Therefore, a method is employed in the present study that addresses the temporal changes in the utilization of various energy sources. Presuming that energy demand and primary energy factors are known for each hour of the year, the annual (8760 h) primary energy demand Q_{pr} can be calculated from

$$Q_{pr} = \sum_{i=1}^{8760} (Q_{fuel,i} PER_{fuel,i} + W_{grid,i} PER_{grid,i}) \quad (12)$$

where $Q_{fuel,i}$ and $W_{grid,i}$ are the fuel consumption of the micro-cogeneration system and the electricity purchased from the grid, respectively, and $PER_{fuel,i}$ and $PER_{grid,i}$ are the primary energy factors for the fuel used by the system and the grid electricity during the i th hour, respectively. Correspondingly, the carbon dioxide emissions are obtained from

$$CO_2 = \sum_{i=1}^{8760} (Q_{fuel,i} CO_{2,fuel,i} + W_{grid,i} CO_{2,grid,i}) \quad (13)$$

where $CO_{2,fuel,i}$ and $CO_{2,grid,i}$ are the carbon dioxide emission factors for the fuel used by the system and the grid electricity during the i th hour, respectively.

Given that one primary energy and emission factor can be assigned to one source of energy j in an electricity production mix with n energy sources, the total primary energy factor for grid electricity is

$$PER_{grid} = \sum_{j=1}^n r_j PER_j \quad (14)$$

and the emission factor is

$$CO_{2,grid} = \sum_{j=1}^n r_j CO_{2,j} \quad (15)$$

where r_j is the ratio of the energy source j in the energy mix and PER_j and $CO_{2,j}$ are the individual primary energy and emission factors for the energy source j , respectively.

The temporal variations in the primary energy and emission factors of fuels are only associated with possible changes in supply chains and their impact on the absolute value of the factors is relatively small. Hence, it is reasonable to use average values in the above assessment instead of trying to figure out exact (hourly) numbers. Average non-renewable primary energy (NRPE), total primary energy (TOTPE), and CO₂ emission factors for various energy forms are summarized in Table 1.

2.7. Economic analysis

The necessary condition for the economic viability of a micro-cogeneration system is that annual savings occur as a result of the improvements in energy efficiency and the potential to use cheaper fuels as substitutes for expensive grid electricity or to receive some compensation for the electricity fed into the grid. In the present study, we first test the above condition by multiplying the annual amount of energy purchased for each micro-cogeneration alternative (obtained from the simulations) by the reference price of a given source of energy (fuel or grid electricity). If an alternative fulfills the condition at a reasonably high annual saving, a simple payback analysis is conducted to further evaluate the financial viability of micro-cogeneration.

Here, if the discounted, cumulated savings during an approved period of time (payback period) equal the capital investment of the micro-cogeneration system, the investment is considered economically feasible. The condition is satisfied if:

$$C_{I,CHP} - \frac{(1+r)^n - 1}{r(1+r)^n} S_{a,CHP} = 0 \quad (16)$$

Table 1
Primary energy factors and CO₂ production coefficients [27–29].

	NRPE	TOTPE	CO ₂
Fuel oil	1.35	1.35	330
Gas	1.36	1.36	277
Natural gas	1.14		247
Wood shavings	0.06	1.06	4
Log	0.09	1.09	14
Hydro electricity	0.5	1.5	7
Nuclear electricity	2.8	2.8	16
Coal electricity	4.05	4.05	1340
UCPTE electricity mix	3.14	3.31	617
EU-17 grid electricity	2.35		430

Table 2
Occupancy patterns.

	The building is occupied between
Profile 1	6:00...8:00 AM and 3:00...23:00 PM
Profile 2	22:00 PM...8:00 AM
Profile 3	5:00...22:00 PM

where $C_{i,CHP}$ is the capital investment of the micro-cogeneration system, $S_{a,CHP}$ is the annual savings during the given time period n , and r is the real interest rate. This approach ignores possible additional costs, such as maintenance and repairs.

3. Computational study

3.1. Building description

The target building is a two-floor single-family house with a heated area of 145.4 m², occupied by four persons following three different profiles that apply on a daily basis (Table 2). The above model is employed to represent the unit module (one apartment) in the evaluation of multi-family houses and groups of buildings, too. The reference location is Helsinki, Finland, and the weather data for 2001 are used. The building is equipped with central mechanical supply and exhaust ventilation (constant air volume of 53 dm³ s⁻¹) with heat recovery (efficiency 60%), and a hydronic heating system.

3.2. Energy demand

The heating system has been given a set point to maintain the room temperature of 21.5 °C. The building does not contain a cooling system, so the temperature rises during the summer months. The electrical demand of the lighting and appliances is defined as the sum of the power requirements of single devices (100 W) according to the profiles of occupancy, as well as the use of domestic hot water. Electrical and domestic hot water demand profiles are shown in Fig. 2. Energy demands per m² of reference area, heat transfer coefficients (U -values), and solar heat gain coefficients (G -

Table 3
Energy demands, heat loss coefficients, and solar heat gain coefficients.

	Standard house	Passive house
Space heat demand (kW h m ⁻² a ⁻¹) ^b	67.9 (244.4)	32.2 (115.9)
Electricity demand (kW h m ⁻² a ⁻¹) ^b	32.2 (115.9)	32.2 (115.9)
U -value exterior wall (W m ⁻² K ⁻¹)	0.21	0.07 ^a
U -value roof (W m ⁻² K ⁻¹)	0.11	0.06
U -value ground floor (W m ⁻² K ⁻¹)	0.16	0.08
U -value door (W m ⁻² K ⁻¹)	1.10	0.40
G -value glazing (-)	0.56	0.46

^a Insulation thickness 600 mm.

^b The values in SI units (MJ) are given in parentheses. The conversion factor is 1 kW h = 3.6 MJ.

values) are summarized in Table 3 for both normal and passive building constructions.

3.3. System description and micro-cogeneration strategies

The micro-cogeneration plant is connected to a hydronic heating system via a buffer storage that allows the parallel application of more than one thermal source and can be set to operate at constant power or to follow the electrical or thermal load or both. The threshold values for temperatures and electrical/thermal power are given as set points to determine whether the device is activated or deactivated. In the event of a thermal surplus or thermal shortage, the device is either deactivated or an auxiliary burner is started to ensure sufficient heat generation. The excess electricity is fed into the battery if possible; otherwise, the system is shut down. The skin losses are released to the room surrounding the plant, which allows them to be utilized in heating up neighboring rooms and pre-heating the combustion air. The integration of the engine model into the heat distribution system is illustrated in Fig. 3.

The reference system is a hydronic heating system with a gas boiler with a constant efficiency of 90% (LHV; LHV = 12.9 kW h kg⁻¹ = 46.4 MJ kg⁻¹), accounting for the losses related to maintaining the temperature of the boiler. The reference efficiency is based on Section D5 of the National Building Code of Finland, where the annual efficiency of a gas or oil boiler with a thermal power less than 35 kW is mentioned as varying between 87% (non-condensing boilers) and 93% (condensing boilers) [30].

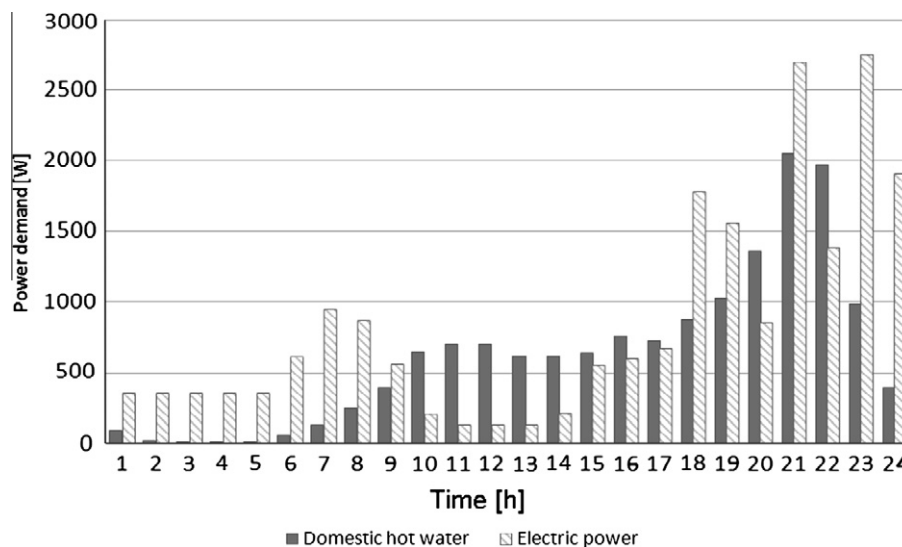


Fig. 2. Hourly power consumption schedules for domestic hot water and electric power demand.

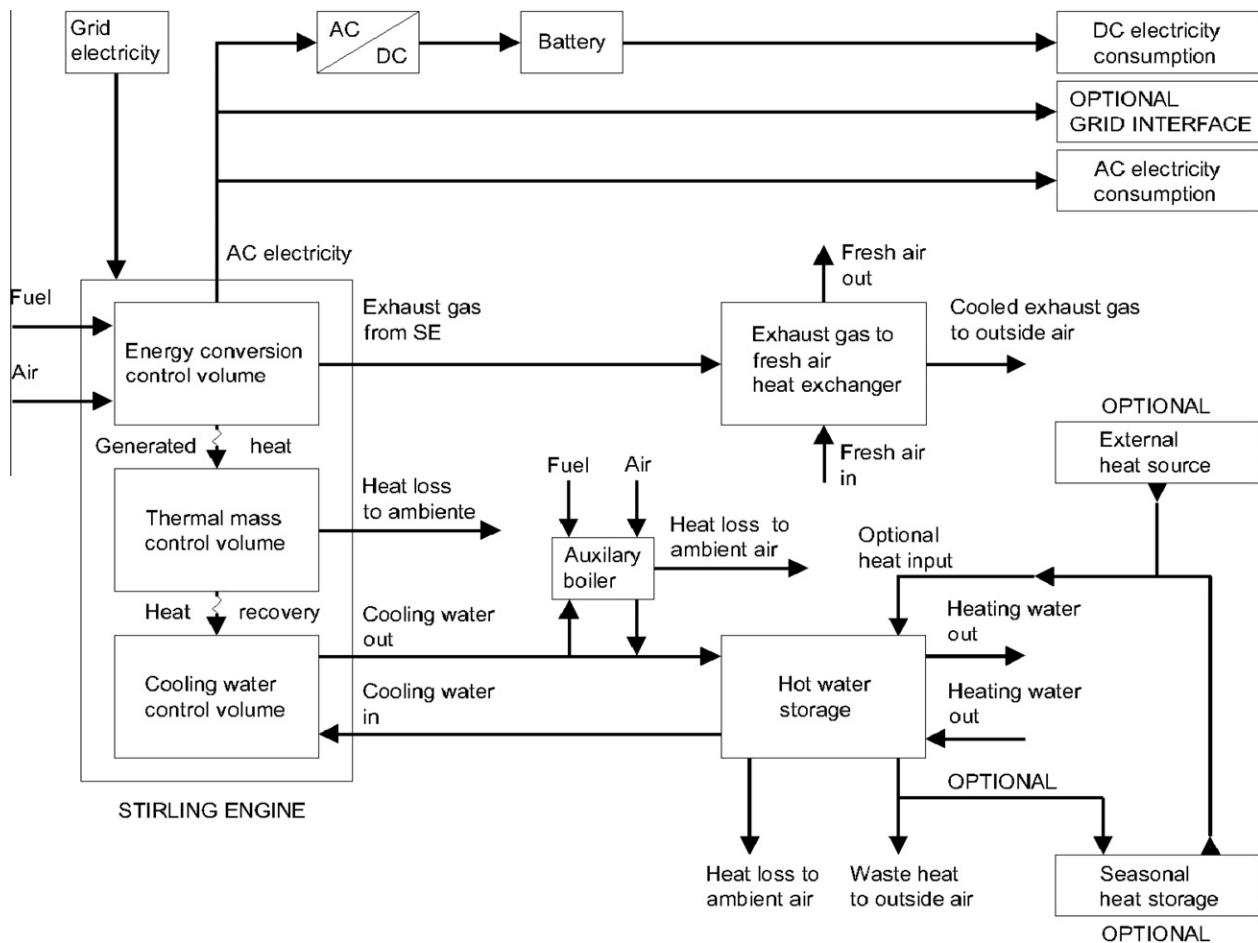


Fig. 3. Integration of the engine model.

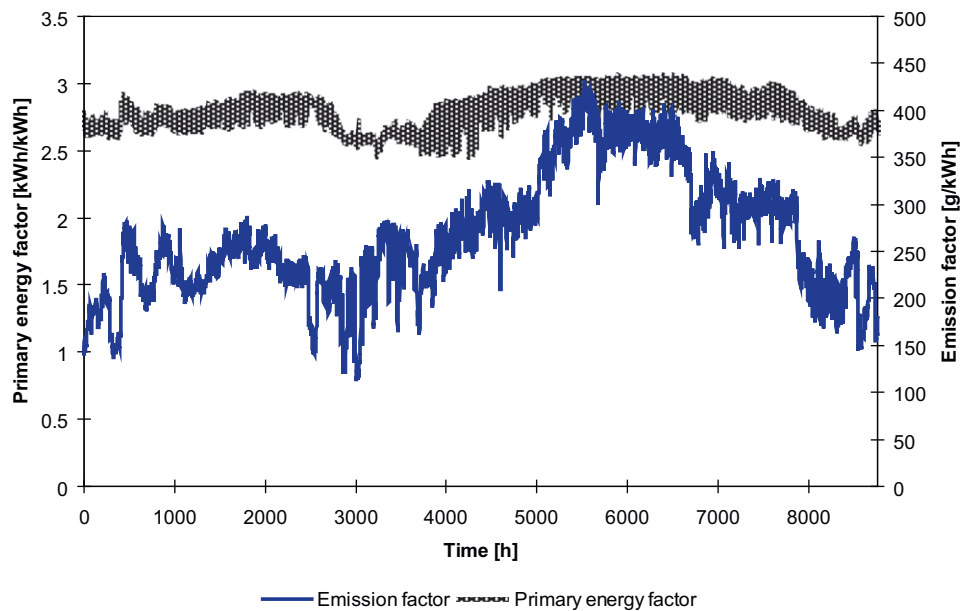


Fig. 4. Hourly primary energy and emission factors of Finnish electricity mix in 2006.

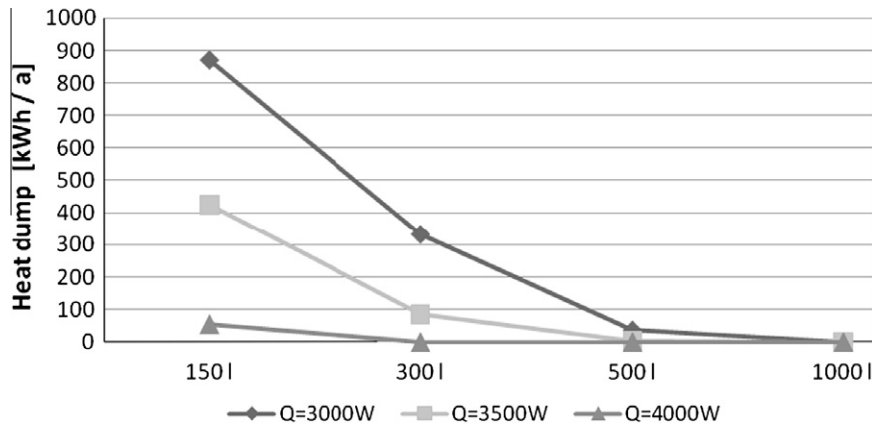


Fig. 5. The impact of the buffer storage tank size and the threshold value of thermal power on the amount of thermal energy dumped to the ambient air during the simulation period of one year.

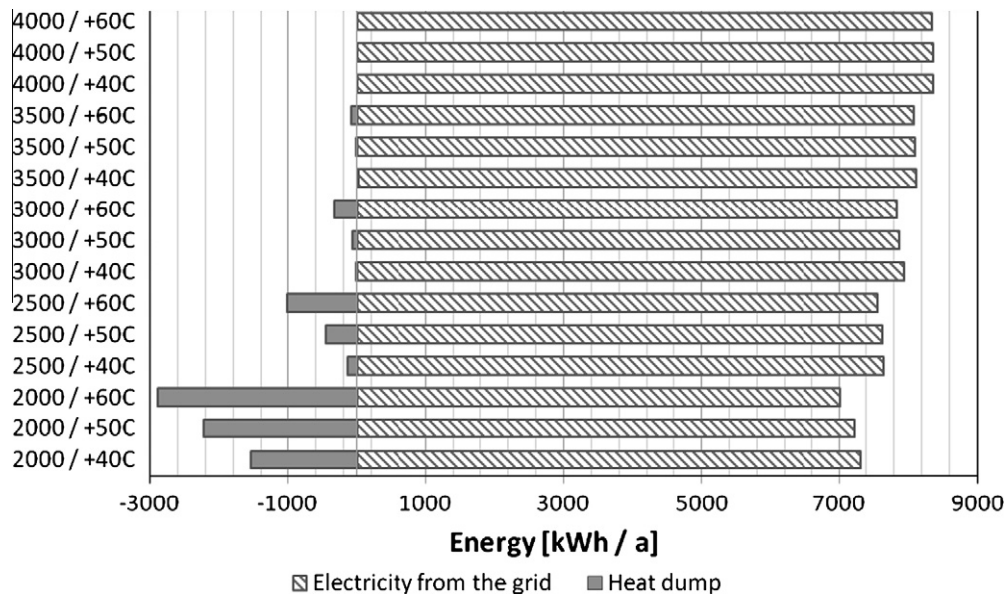


Fig. 6. The annual amount of electricity to be bought from the grid and the heat dumped from the storage tank. Different storage tank temperatures (40–60) and thermal threshold powers (2000–4000 W) are included in the study.

3.4. Primary energy and emission profiles

The primary energy and emission factors for each hour were calculated by way of a spreadsheet application, following the principles in Section 2.4. The Finnish electricity production mix for the year 2006 was determined using measured hourly electricity generation data in Finland (coverage: 99% of the plants), plus imports and exports inside the Nordic electricity market. The source of these data is Finnish Energy Industries (ET). The profiles derived from these data are shown in Fig. 4.

3.5. Energy prices

To assess the economic value of the savings, the typical Finnish price for a small natural gas user is applied as a reference, i.e. 0.04 € kW h^{-1} .¹ The reference price for grid electricity is valued at 0.10 € kW h^{-1} .

¹ Vattenfall, representing a large company providing gas for private customers, charges $0.0423 \text{ € kW h}^{-1}$, while Valkeakaasu, a corresponding small-sized company, charges $0.0449 \text{ € kW h}^{-1}$.

4. Results

4.1. System configuration and operational strategies

In the normal operating mode the engine is controlled in a manner consistent with the electric and thermal power requirements. That is, the engine is operational if either the electrical or thermal power requirements or both of these exceed the set-point value, i.e. the threshold value. Hence, the optimal system configuration and operational strategy in the present approach incorporates threshold values for both electrical and thermal power, optimal sizes for storage tanks, and the effect of heat recovery from the exhaust gases. The aim of the optimization is to avoid the annual use of grid electricity and thermal dumping. These objectives are contradictory, because increasing the electricity generation by micro-cogeneration results in a greater thermal excess. The optimum can be found by both sizing the system correctly and determining the relevant activation and deactivation periods.

The impact of the buffer storage tank size and the threshold value of thermal power on the amount of thermal energy dumped to

the ambient air during the simulation period of one year are presented in Fig. 5.

A conclusion can be drawn from Fig. 5 that the effect of the threshold value on heat dumping is greater at smaller tank sizes. In the present application, zero heat dumping is obtained at the tank size of 500 L (dm³) if the threshold thermal power is more than 3.5 kW. Increasing the thermal threshold value limitlessly, however, deprives micro-cogeneration of its advantage in electricity production. Therefore, some heat dumping may be acceptable if purchasing grid electricity can be avoided by an amount that exceeds the environmental burden or costs caused by the corresponding amount of fuel.

The annual grid electricity and thermal dumping dependence for various thermal threshold powers and storage tank temperatures is summarized in Fig. 6.

As shown in Fig. 6, the thermal dumping increases significantly if the threshold value is changed from 2.5 kW to 2.0 kW, whereas the amount of electricity purchased only decreases slightly. This implies that the thermal threshold value should be higher than 2 kW, but, on the other hand, it does not need to be more than 3.5 kW to eliminate the heat dumping. Similar conclusions can also be drawn by looking at the annual costs that are presented in Fig. 7.

The information in Fig. 7 also provides a reason for concluding that the lower the thermal power threshold value is, the greater the significance that the electric power threshold value has. When the thermal threshold value exceeds 3 kW, the minimum operational costs are achieved and they are, in fact, equal to any electric power threshold value.

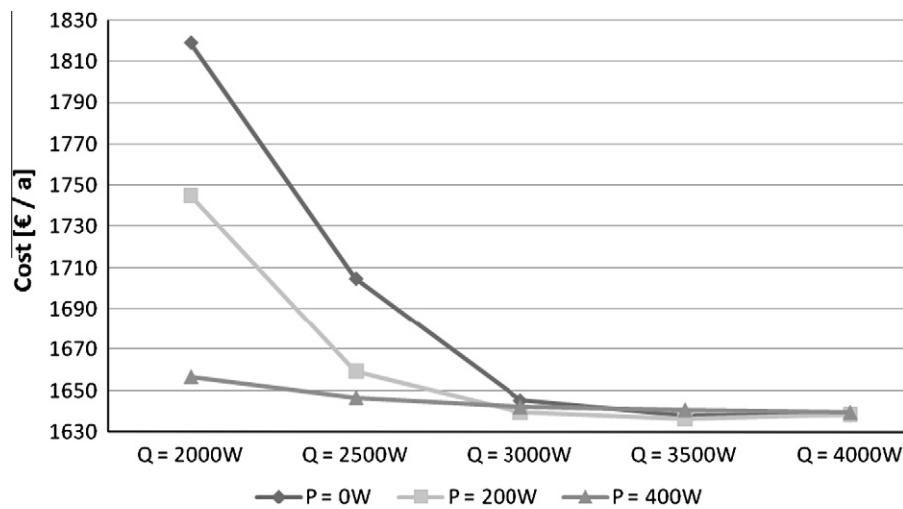


Fig. 7. Operating costs per year for three different electric power thresholds. The results are shown as a function of the thermal power threshold value.

Table 4

Primary energy use and CO₂ emissions for the standard house.

Helsinki	REF	1	2	3	4	5	6	7
Grid electricity (kW h a ⁻¹)	8283 (30 GJ)	8283 (30 GJ)	7821 (28 GJ)	7892 (28 GJ)	7659 (28 GJ)	7517 (27 GJ)	7582 (27 GJ)	7641 (28 GJ)
Fuel (kW h a ⁻¹)	18,152 (65 GJ)	17,482 (63 GJ)	19,802 (71 GJ)	19,030 (69 GJ)	19,278 (69 GJ)	19,081 (69 GJ)	18,026 (65 GJ)	19,428 (70 GJ)
Annual primary energy (kW h a ⁻¹)	42,235 (152 GJ)	43,511 (157 GJ)	42,857 (154 GJ)	42,485 (153 GJ)	41,872 (151 GJ)	40,891 (147 GJ)	42,602 (153 GJ)	41,000 (148 GJ)
Annual CO ₂ emissions (kg a ⁻¹)	5692	6063	5927	5910	5836	5643	5918	5647
Annual primary energy (kW h a ⁻¹ m ⁻²)	290.5 (1046 GJ)	299.3 (1077 GJ)	294.8 (1061 GJ)	292.2 (1052 GJ)	288.0 (1037 GJ)	281.2 (1012 GJ)	293.0 (1055 GJ)	282.0 (1015 GJ)
Annual CO ₂ emissions (kg a ⁻¹ m ⁻²)	39.1	41.7 (+6.5%)	40.8 (+4.1%)	40.6 (+3.8%)	40.1 (+2.5%)	38.8 (−0.9%)	40.7 (+4.0%)	38.8 (−0.8%)
Jyväskylä	REF	1	2	3	4	5	6	7 ^c
Grid electricity (kW h a ⁻¹)	8248 (30 GJ)	N/A	N/A	7314 (26 GJ)	7500 (27 GJ)	7579 (27 GJ)	7315 (26 GJ)	7261 (26 GJ)
Fuel (kW h a ⁻¹)	20,645 (74 GJ)	N/A	N/A	23,194 (83 GJ)	21,989 (79 GJ)	20,427 (74 GJ)	23,053 (83 GJ)	21,126 (76 GJ)
Annual primary energy (kW h a ⁻¹)	45,618 (164 GJ)	N/A	N/A	45,832 (165 GJ)	45,030 (162 GJ)	43,527 (157 GJ)	45,689 (164 GJ)	43,409 (156 GJ)
Annual CO ₂ emissions (kg a ⁻¹)	6308	N/A	N/A	6601	6407	6116	6556	6161
Annual primary energy (kW h a ⁻¹ m ⁻²)	313.7 (1129 GJ)	N/A	N/A	315.2 (1135 GJ)	309.7 (1115 GJ)	299.4 (1078 GJ)	314.2 (1131 GJ)	298.6 (1075 GJ)
Annual CO ₂ emissions (kg a ⁻¹ m ⁻²)	43.4	N/A	N/A	45.4 (+4.6%)	44.1 (+1.6%)	42.1 (−3.1%)	45.1 (+3.9%)	42.4 (−2.3%)

^c Mandatory period of operation of 2.0 h during peak demand hours between April 1 and October 31.

Table 5Primary energy use and CO₂ emissions for the passive house.

Helsinki	REF	1	2	3	4	5
Grid electricity (kW h a ⁻¹)	8227 (30 GJ)	8077 (29 GJ)	7977 (29 GJ)	8091 (29 GJ)	8311 (30 GJ)	8064 (29 GJ)
Fuel (kW h a ⁻¹)	11,035 (40 GJ)	11,519 (41 GJ)	11,473 (41 GJ)	12,192 (44 GJ)	11,078 (40 GJ)	11,507 (41 GJ)
Annual primary energy (kW h a ⁻¹)	34,986 (126 GJ)	35,105 (126 GJ)	34,770 (125 GJ)	35,895 (129 GJ)	35,269 (127 GJ)	35,055 (126 GJ)
Annual CO ₂ emissions (kg a ⁻¹)	4399	4466	4426	4599	4431	4462
Annual primary energy (kW h a ⁻¹ m ⁻²)	240.6 (866 MJ)	241.4 (869 MJ) (+0.3%)	239.1 (861 MJ) (-0.6%)	246.9 (889 MJ) (+2.6%)	242.6 (873 MJ) (+0.8%)	241.1 (868 MJ) (+0.2%)
Annual CO ₂ emissions (kg a ⁻¹ m ⁻²)	30.3	30.7 (+1.5%)	30.4 (+0.6%)	31.6 (+4.6%)	30.5 (+0.7%)	30.7 (+1.4%)

4.2. Primary energy demand and emissions

Primary energy demand and emissions were ascertained for two energy demand levels (a standard single-family house) and two different climates (Helsinki and Jyväskylä).

Referring to the conclusions drawn in Section 4.1, seven alternative micro-cogeneration schemes were assessed in the standard house:

1. threshold values 200 W and 3000 W electrical and thermal, respectively/no thermal storage/no heat recovery from exhaust gases,
2. 200 W/3000 W/no thermal storage/heat recovery,
3. 200 W/3500 W/thermal storage 500 L/no heat recovery,
4. 200 W/3500 W/500 L/heat recovery,
5. 200 W/3500 W/500 L/heat recovery (with buffer storage of 500 L),
6. 200 W/4000 W/300 L/heat recovery (300 L)/mandatory operation of 2 h during peak demand hours between April 1 and October 31,
7. 200 W/3500 W/500 L/heat recovery (500 L)/mandatory operation of 2.5 h during peak demand hours between April 1 and October 31.

The energy use, annual primary energy demand, and emissions are summarized in Table 4.

The data in Table 4 indicate that without thermal storage the micro-cogeneration system is not capable of reducing the primary energy demand and emissions when compared to the reference system. In both climates Options 5 and 7 cut emissions and primary energy demand by at most 5%, which is in line with other studies [3,8–10]. Both schemes include heat recovery from the exhaust gases and a thermal storage tank with a capacity of 500 L. Moreover, Option 4 mitigates the primary energy demand when compared to the reference system.

So-called passive houses are a more challenging environment for Stirling engine-based micro-cogeneration than standard houses, because less thermal energy is demanded with respect to electricity. On the other hand, the Stirling engine's electrical efficiency is low, whereas a large ratio of the fuel's energy is converted to thermal power. Considering this, we assessed the following micro-cogeneration schemes for the passive house.

1. Floor heating/200 W and 2500 W electrical and thermal, respectively/thermal storage 500 L/heat recovery (no buffer storage)/domestic hot water (DHW) tank 150 L.
2. Floor heating/200 W/2500 W/500 L/heat recovery (500 L)/DHW 150 L/mandatory operation of 1 h during peak demand hours between April 1 and October 31.
3. Radiator heating/200 W/4000 W/300 L/no heat recovery/mandatory operation of 1 h during peak demand hours between April 1 and October 31, 2 h on the heating period (November 1–March 31).

4. Radiator heating/200 W/4000 W/300 L/heat recovery (no buffer storage).
5. Radiator heating/200 W/2500 W/300 L/heat recovery (500 L).

The results are shown in Table 5.

Micro-cogeneration increases both the primary energy demand and emissions in each of these cases. Option 2 results in a decrease, but only by 0.6%. Henceforth, these results support the presumption that current prototype Stirling engines perform poorly for the co-production of electricity and heat in passive buildings.

4.3. Economic viability

One of the most important advantages of a Stirling engine is its ability to utilize various fuels. Therefore, we investigated the economic viability of Stirling engine micro-cogeneration especially from the viewpoint of a reference system being replaced by a micro-cogeneration system using the same fuel. Here, systems using natural gas, oil, wooden pellets, and electricity were examined and all the operational cost savings were referred to the configuration employing an exhaust gas heat recovery system. Only the standard house constructions were included in the analysis because of the inferior attainable savings in comparison with the reference heating system in the passive house. An energy price of 0.040 € kW h⁻¹ was applied for natural gas, 0.048 € kW h⁻¹ for pellets, 0.057 € kW h⁻¹ for oil, and 0.010 € kW h⁻¹ for electricity. The payback periods were taken as being 5, 10, 15, and 20 years and a real interest rate of either 1% or 5% was used.

The discounted savings in Helsinki and in Jyväskylä are shown in Figs. 8 and 9, respectively. The figures depict the greatest accumulated savings of an SE-based micro-CHP system, which, in turn, represents the maximum approvable capital cost invested in micro-cogeneration to keep the option financially viable in comparison to traditional heating systems.

Consistent with these values, the greatest savings are reached in comparison to electrical hydronic heating, where savings up to 10,900€ and 13,600€ are obtained with a payback time of 10 years and the real interest rate of 2% in Helsinki and Jyväskylä, respectively. Probably a more realistic comparison is that between micro-cogeneration and oil heating plus grid electricity, where the corresponding savings are 3300€ and 4400€. In comparison with wooden pellet heating, the savings are 1600€ and 2400€, but with natural gas heating only 200€ and 700€.

As shown in Fig. 8, the above analysis is not very sensitive to electricity prices. On the other hand, payback periods of more than 10 years may not be justifiable if the issue is about updating an existing heating system to micro-cogeneration in terms of a refurbishment project.

4.4. Sensitivity analysis

As can be inferred from Fig. 4, the primary energy and emission factors depend heavily on the variations in the energy mix during a

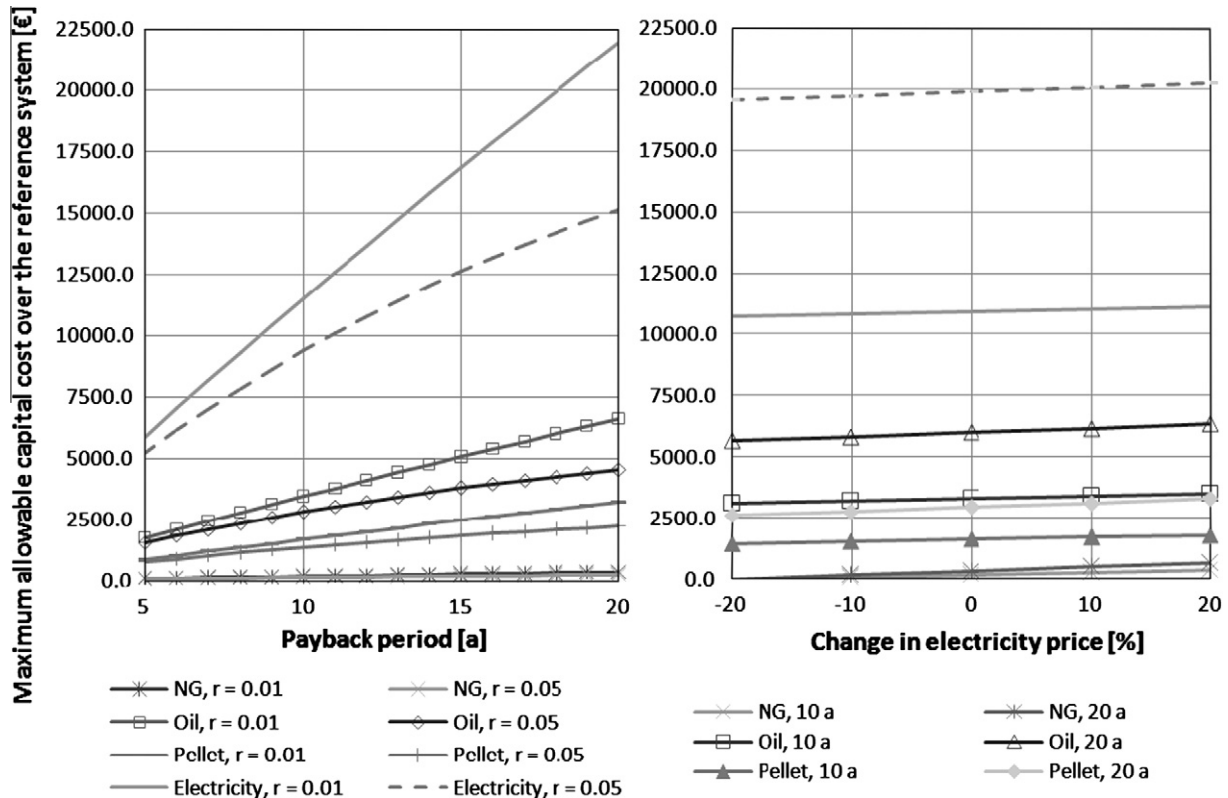


Fig. 8. The effect of payback period and electricity price (real interest rate of 2%) on the accumulated savings of SE micro-cogeneration located in Helsinki.

year, which, in turn, relates to the supply (availability) and demand (need for instantaneous power on a national scale) of different forms of energy. On the other hand, for the same reason the above results are not applicable to similar buildings in corresponding latitudes and climates. Motivated by these premises, a sensitivity analysis was conducted to bring the results into a more general frame in a European context. The analysis accounted for the annual energy purchased and fuel consumed in the reference case and micro-cogeneration schemes 5 and 7, presuming that the grid electricity originates from various sources. The results of the analysis are summarized in Table 6.

Assuming that all the grid electricity was generated by hydro power, the reference system would fall short of any micro-cogeneration systems in primary energy use in Helsinki. In Jyväskylä, on the other hand, micro-cogeneration scheme 5 would be the optimal choice in this case.

Compared to nuclear power, scheme 5 showed a decrease in the primary energy consumption in Helsinki, whereas all the schemes would cut some primary energy in Jyväskylä. CO₂ emissions could not be mitigated in this scenario either in Helsinki or Jyväskylä.

Micro-cogeneration would, as expected, provide an advantage in curbing both primary energy consumption and emissions if all the grid electricity were generated by coal. A similar trend can be observed when comparing the primary energy and emissions of micro-cogeneration schemes with those of the reference system and average grid electricity (EU-17 and Union for the Co-ordination of Production and Transmission of Electricity, UCPTE).

Overall, the above considerations show that micro-cogeneration might possess some potential to cut primary energy use and emissions in Finland and that scheme 5 would be slightly preferred. Finally, the conclusion can also be drawn that the curbing potential is narrow and depends significantly on which kind of grid electricity production structure the comparison is based on. The result of

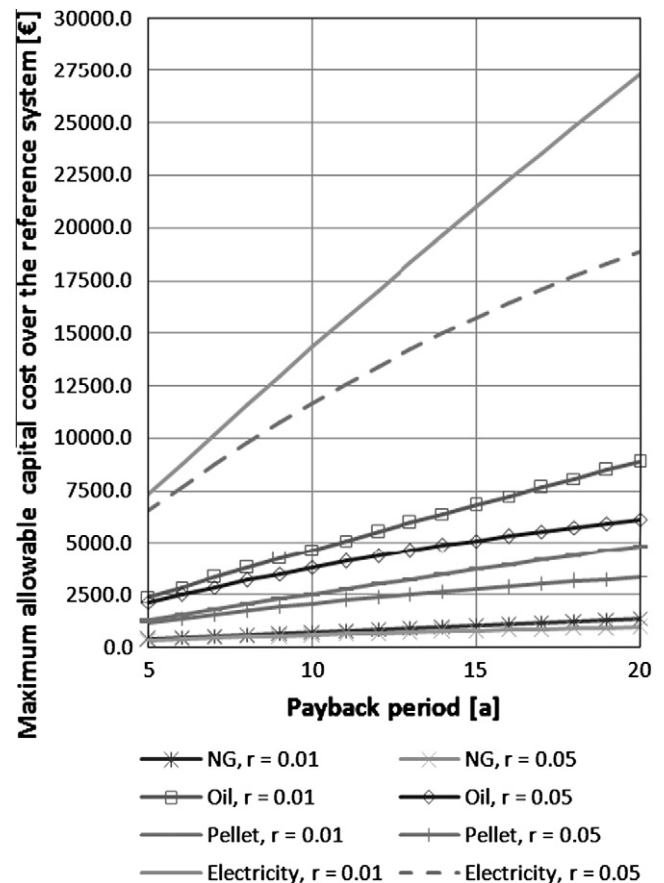


Fig. 9. The effect of payback period and electricity price (real interest rate of 2%) on the accumulated savings of SE micro-cogeneration located in Jyväskylä.

Table 6

Annual primary energy use and emissions.

	REF (MJ)	5 (MJ)	7 (MJ)
<i>Primary energy use (kW h a⁻¹ m⁻²)</i>			
Helsinki			
Hydro electricity	192 (691)	195 (702)	196 (706)
Nuclear electricity	323 (1163)	315 (1134)	316 (1138)
Coal electricity	394 (1418)	380 (1368)	381 (1372)
UCPTE electricity mix	342 (1231)	332 (1195)	333 (1199)
EU-17 grid electricity	297 (1069)	291 (1048)	292 (1051)
Jyväskylä			
Hydro electricity	221 (796)	217 (781)	223 (803)
Nuclear electricity	352 (1267)	337 (1213)	337 (1213)
Coal electricity	423 (1523)	402 (1447)	400 (1440)
UCPTE electricity mix	371 (1336)	355 (1278)	354 (1274)
EU-17 grid electricity	326 (1174)	314 (1130)	315 (1134)
<i>CO₂ emissions (kg a⁻¹ m⁻²)</i>			
Helsinki			
Hydro electricity	34	35	35
Nuclear electricity	34	35	35
Coal electricity	110	104	104
UCPTE electricity mix	68	67	67
EU-17 grid electricity	58	57	57
Jyväskylä			
Hydro electricity	40	39	41
Nuclear electricity	40	40	41
Coal electricity	115	109	107
UCPTE electricity mix	74	71	71
EU-17 grid electricity	64	61	62

this analysis also supports the conclusion that for the performance level of the current prototypes, the breakthrough of micro-cogeneration in Finland is challenging.

The economic analysis showed that the restricting issue for the economic viability of micro-cogeneration is more probably whether it creates monetary savings with respect to the reference

system than if the payback period is within an acceptable range. Hence, there is a “break-even” combination of fuel and electricity prices where the viability condition is fulfilled. The annual cost savings of the micro-generation scheme 5 for various fuel price and electricity price combinations in Helsinki and Jyväskylä are summarized in Table 7.

In Table 7, the savings are presented in such a manner that electricity and fuel prices vary between 0.05 and 0.15 € kW h⁻¹. For example, in Helsinki the combination of an electricity price of 10 € kW h⁻¹ and a fuel price of 5 € kW h⁻¹ results in an annual saving of 43 € a⁻¹.

As shown in Table 7, micro-cogeneration scheme 5 always generates annual savings with respect to the reference case in Jyväskylä. It is interesting to note that in Jyväskylä the annual savings also increase along with an increase in the fuel price, although in a moderate way. The above indicates that the savings in fuel consumption are even higher than the benefit obtained by avoiding purchasing electricity from the grid, which implies that the operation of micro-cogeneration according to threshold values throughout the year is preferable to the application of mandatory operational periods.

In general, the price of fuel has so far been lower than that of electricity and there is a correlation between the prices. These statistical effects were not examined here in detail. Neither did the present analysis take into account the option of delivering electricity to the grid in return for monetary compensation. This possibility would have probably improved the viability of micro-cogeneration, but in the applied case the nominal power of the equipment is sufficiently low that the issue did not prove to be critical. Simulation errors cause an additional source of uncertainty in this type of study. The variation between actual energy demand and energy demand estimated on the basis of dynamic, whole-building simulations may be up to ±10%, but the best agreements lay within ±3% [31,32]. Hence, a separate uncertainty analysis was not included in this study.

Table 7

Annual cost savings of micro-cogeneration scheme 5.

Cost savings (€ a ⁻¹)											
Helsinki											
	Electricity (€ kW h ⁻¹)										
Fuel (€ kW h ⁻¹)	0.05	0.06	0.07	0.08	0.09	0.1	0.11	0.12	0.13	0.14	0.15
0.05	8	15	22	29	36	43	50	57	64	71	78
0.06	2	9	16	23	30	37	44	51	58	65	72
0.07	-3	4	11	18	25	32	39	46	53	60	67
0.08	-8	-1	6	13	20	27	34	41	48	55	62
0.09	-14	-7	0	7	14	21	28	35	42	49	56
0.10	-19	-12	-5	2	9	16	23	30	37	44	51
0.11	-25	-18	-11	-4	3	10	17	24	31	38	45
0.12	-30	-23	-16	-9	-2	5	12	19	26	33	40
0.13	-36	-29	-22	-15	-8	-1	6	13	20	27	34
0.14	-41	-34	-27	-20	-13	-6	1	8	15	22	29
0.15	-46	-39	-32	-25	-18	-11	-4	3	10	17	24
Jyväskylä											
	Electricity (€ kW h ⁻¹)										
Fuel (€ kW h ⁻¹)	0.05	0.06	0.07	0.08	0.09	0.1	0.11	0.12	0.13	0.14	0.15
0.05	44	51	58	64	71	78	85	91	98	105	111
0.06	47	53	60	67	73	80	87	93	100	107	113
0.07	49	55	62	69	76	82	89	96	102	109	116
0.08	51	58	64	71	78	84	91	98	104	111	118
0.09	53	60	66	73	80	87	93	100	107	113	120
0.10	55	62	69	75	82	89	95	102	109	116	122
0.11	57	64	71	78	84	91	98	104	111	118	124
0.12	60	66	73	80	86	93	100	107	113	120	127
0.13	62	69	75	82	89	95	102	109	115	122	129
0.14	64	71	77	84	91	97	104	111	118	124	131
0.15	66	73	80	86	93	100	106	113	120	126	133

5. Conclusions

This paper focuses on searching for optimized strategies for the integration of a Stirling engine-based micro-cogeneration system in residential buildings. The study contributes to the improvements obtained by adaptation to hourly changes in the energy generation mix and the utilization of thermal exhaust through heat recovery. The computational results imply that an optimally operated micro-cogeneration system encompassing heat recovery and relevant thermal storages could result in a 3–5% decrease in primary energy consumption and CO₂ emissions when compared to a conventional hydronic heating system. This is in line with other European performance assessments. Moreover, the above configuration is capable of creating annual savings in all the combinations of electricity and fuel price between 5 and 15 c kW h⁻¹. Ignoring maintenance and repair costs, in Finland a realistic approximate for the cumulative savings over a period of 10 years and with a real interest rate of 2% is 3000–4000€, when a Stirling engine micro-cogeneration system is considered as an alternative to oil heating.

The above result is sensitive to the energy mix, building type, and climate. Natural gas-burning Stirling engine micro-cogeneration works best in standard houses in cold climates with the present (or even more coal-based) electricity mixes, but, as expected, applies poorly to a passive house, where the electrical power demand is high when compared to that for thermal power. An increase in the use of renewable energy sources in electricity generation may deprive Stirling engine micro-cogeneration of its benefit. A similar outcome can be associated with an increase in nuclear power. The Nordic countries, where the ratio of non-carbon electricity power is high, are therefore among the most challenging market areas for combustion-based micro-cogeneration and a lot depends on which thermal source is used to fuel the micro-cogeneration system.

There are several avenues for further research. The topic will be extended to local grids, where more than one building is served by one micro-cogeneration plant. Likewise, the effects of the large-scale penetration of micro-cogeneration into the national energy grids should be investigated in terms of how the primary energy and emissions profiles are determined. Here, the concept of micro-cogeneration will also be widened to various technologies, hybrid systems where solar and micro-wind power are integrated into one system, and the simultaneous production of more than two “forms” of energy, the so-called poly-generation.

References

- [1] Intergovernmental Panel on Climate Change (IPCC). Climate change 2001: mitigation, contribution of working group III to the third assessment report of the intergovernmental panel on climate change. United States of America: Cambridge University Press; 2001.
- [2] Andreassi L, Ciminelli MV, Feola M, Ubertini S. Innovative method for energy management: modelling and optimal operation of energy systems. *Energy Build* 2009;41:436–44.
- [3] Dorer V, Weber R, Weber A. Performance assessment of fuel cell micro-cogeneration systems for residential buildings. *Energy Build* 2005;37:1132–46.
- [4] Alanne K, Saari A. Distributed energy generation and sustainable development. *Renew Sust Energy Rev* 2006;10:539–58.
- [5] Alanne K, Saari A. Sustainable small-scale CHP technologies for buildings: the basis for multi-perspective decision-making. *Renew Sust Energy Rev* 2004;8:401–31.
- [6] Beausoleil-Morrison I, editor. An experimental and simulation-based investigation of the performance of small-scale fuel cell and combustion-based cogeneration devices serving residential buildings, final report of Annex 42 of the international energy agency's energy conservation in buildings and community systems programme, the government of Canada; 2008. ISBN:978-0-662-47923-9.
- [7] Ferguson A, Kelly N, Weber A, Griffith B. Modelling residential-scale combustion-based cogeneration in building simulation. *J Build Perform Simulat* 2009;2:1–14.
- [8] Dorer V, Weber A. Energy and CO₂ emissions performance assessment of residential micro-cogeneration systems with dynamic whole-building simulation programs. *Energy Convers Manage* 2009;50:648–57.
- [9] Peacock AD, Newborough M. Impact of micro-combined heat-and-power systems on energy flows in the UK electricity supply industry. *Energy* 2006;31:1804–18.
- [10] Ribberink H, Bourgeois D, Beausoleil-Morrison I. A plausible forecast of the energy and emissions performance of mature-technology Stirling engine residential cogeneration systems in Canada. *J Build Perform Simulat* 2009;2:47–61.
- [11] Hawkes A, Leech M. Impacts of temporal precision in optimisation modelling of micro-combined heat and power. *Energy* 2005;30:1759–79.
- [12] Onovwiona HI, Ugursal VI, Fung AS. Modeling of internal combustion engine based cogeneration systems for residential applications. *Appl Therm Eng* 2006;27:848–61.
- [13] Björnsell N, Bring A, Ericsson L, Grozman P, Lindgren M, Sahlin P et al. IDA indoor climate and energy. In: Proceedings of the IBPSA building simulation '99 conference, Kyoto, Japan; 1999.
- [14] Sahlin P. Modelling and simulation methods for modular continuous system in buildings. Doctoral thesis, KTH, Stockholm; 1996.
- [15] Achermann M, Zweifel G. RADTEST – radiant heating and cooling test cases. Subtask C. A report of IEA task 22. Building energy analysis tools IEA; 2003.
- [16] Travesi J, Maxwell GM, Klaassen K, Holtz M. Empirical validation of iowa energy resource station building energy analysis simulation models. A report of IEA task 22. Building energy analysis tools IEA; 2001.
- [17] Beausoleil-Morrison I, Kelly N, Ferguson A, Griffith B, Maréchal F, Weber A. Specifications for modelling fuel cell and combustion-based residential cogeneration devices within whole-building simulation programs. A report of IEA/ECBCS Annex 42, IEA; 2007. ISBN:978-0-662-47116-5.
- [18] Vesanen T, Klobut K, Shemeikka J. Implementation of a fuel cell system model into building energy simulation software IDA-ICE. *J Fuel Cell Sci Technol* 2007;4.
- [19] McCrorie KAB, Underwood WB, le Feuvre RF. Small-scale combined heat and power simulations: development of a dynamic spark ignition engine model. *Build Serv Eng Res Technol* 1996;17:153–9.
- [20] Kelly N. Towards a design environment for building-integrated energy systems: the integration of electrical power flow modeling with building simulation. PhD thesis, University of Strathclyde, Glasgow; 1998.
- [21] Pearce J, Zahawi BA, Shuttleworth R. Energy generation in the home: modelling of single house domestic combined heat and power. *IEEE Proc Sci Meas Technol* 2001;148(5):197–203.
- [22] NIST Chemistry WebBook. NIST standard reference database number 69, National institute of standards and technology, Gaithersburg, MD; 2008. <<http://www.webbook.nist.gov>>.
- [23] Beausoleil-Morrison I, Ferguson A editors. Inter-model comparative testing and empirical validation of Annex 42 models for residential cogeneration devices. A report of IEA/ECBCS Annex 42, IEA; 2007. ISBN:978-0-662-47562-0.
- [24] Alanne K, Söderholm N, Sirén K. Implementation and validation of combustion engine micro-cogeneration routine for the simulation program IDA-ICE. In: Proceedings of the building simulation 2009 conference, Glasgow; 2009.
- [25] Boonekamp PGM. Energy and emission monitoring for policy use trend analysis with reconstructed energy balances. *Energy Policy* 2004;32:969–88.
- [26] Segers R. Three options to calculate the percentage renewable energy: an example for a EU policy debate. *Energy Policy* 2008;36:3243–8.
- [27] Frischknecht R, Bollens U, Bosshart S, Ciot M, Ciseri L, Doka G et al. Ökoinventare von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz, Auflage no. 3, Gruppe Energie – Stoffe – Umwelt (ESU), Eidgenössische Technische Hochschule Zuerich und Sektion Ganzheitliche Systemanalysen, Paul Scherrer Institut, Villigen, Bundesamt für Energie (Hrsg.), Bern; 1996.
- [28] Petersdorff C, Primas A. Appendix A1: primary energy in sustainable solar housing, vol. 1. Strategies & solutions. London: Earthscan Publishers; 2007. ISBN:1844073262.
- [29] GEMIS 2004 Gemis; Global Emission Model for Integrated Systems, Öko-institut, Darmstadt, 2004.
- [30] Finnish Ministry of the Environment. Section D5 of the national building code of Finland – calculation of performance and energy requirement for the heating of buildings, Helsinki; 2007.
- [31] Tuomaala P. Implementation and evaluation of air flow and heat transfer routines for building simulation tools. Doctoral thesis, Helsinki University of Technology, Espoo; 2002.
- [32] Fuehrlein B, Chandra S, Beal D, Parker D, Vieira R. Evaluation of EnergyGauge® USA, a residential energy design software, against monitored data. In: Proceedings of the ACEEE 2000 summer study, American Council for an Energy Efficient Economy, Washington, DC; 2000.